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Growth and characterization of nanoscale thin films

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GROWTH AND CHARACTERIZATION OF NANOSCALE THIN FILMS

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in Partial Fulfillment
of the Requirements for the Designation
University Honors with Distinction

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GROWTH AND CHARACTERIZATION OF NANOSCALE THIN FILMS

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Thin manganese films were grown by thermal evaporation in high vacuum. The growth rate was varied to determine how the growth rate affects the continuity of ultra-thin films. The resistance was measured with the two-point method *in situ* and the data was recorded digitally. The resistance was converted to resistivity and this was plotted against thickness. It was found that resistivity decreases exponentially as the film begins to form in islands. The film reaches a critical thickness as the islands coalesce and the data can then be fitted with Fuchs' equation. The resistivity continues to decrease but the minimum resistivity of the film does not reach bulk resistivity because there are inherent defects in the film

I would like to acknowledge my advisor Dr. Tim Kidd for allowing me to perform this study and helping me along the way. I have learned a great deal about science and life in working with him. I would like to thank my parents, Calvin and Stella, and my sister, Kelly, for helping me to like science and keeping me positive even when times get tough. Thanks also to my fiancée, Annie, for always being there with me and listening to my physics all the time. I would also like to acknowledge support by the Iowa Power Fund and the University Of Northern Iowa Department Of Physics.

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Chapter 1

Purpose

The purpose of the project was to build a vacuum chamber for the growth and study of manganese thin films, specifically electrical and physical properties. The films were grown in the vacuum by thermal evaporation and they were analyzed *in situ* and after growth. Properties of materials at nanoscales differ greatly from the properties of the bulk materials. The unique properties make thin films useful for improving semi-conductors, solar cells, and other electronic devices. Intrinsic properties of manganese change with the thickness of the film, and the goal was to learn about how and at what thickness the changes occur.

Literature Review

Nanoscale structures have been studied for several decades, and they continue to change science and industry^[1]. Nanostructures have been defined to be materials with at least one dimension less than 100 nm in thickness. Nanoscale materials are used in applications including: solar cells^[2], circuits^[3], superconductors^[1], and many other devices^[3, 4]. The properties are being studied and modified to make products faster, smaller, and more efficient.

Thin films are a type of nanoscale structure that have been studied for several decades and Fuchs and Sondheimer found that the resistivity of thin films increases as the thickness decreases^[5]. Resistivity is a measure of a material's opposition to the flow of electric current through its length. Resistivity is defined by the equation,

$$\rho = R \frac{t*w}{\ell}, \quad (1)$$

where R is the resistance of the material (opposition to flow of electric current) that is measured in Ohms; t is thickness, w is the width, and ℓ is the length of the material. Resistivity is a

constant in all materials, except when they are reduced to nano sizes, which was a new discovery. Gold has a resistivity of $2.44 \times 10^{-8} \Omega\text{m}$ no matter how big it is or what shape it is, except when it is a nanostructure. Several studies have discussed explanations of Fuchs' findings^[6], but this study looked at how manganese fits the standard.

The technique used for this experiment was similar to work by Strongin et al. in 1968^[7]. They were studying the effects of the temperature dependence in thin films on resistance, which is a measure of an electrical property that changes with the size of a material. Resistance depends on the size of a material and can vary from 0.2 Ohms/km to 1400 Ohms/km in different copper wires. Strongin evaporated films onto glass substrates in a high vacuum, with low growth rates and temperatures below 10K. Thermal evaporation has been proven to be successful for growing high quality metal films such as manganese^[7-10] and was used in this experiment.

Manganese has previously been studied because of its structural, magnetic, and electronic properties^[8, 9, 11, 12], but not as extensively as gold. The magnetic properties were found to change under a thickness of 1nm and were dependent on the insulating capping layer used to protect the surface of the film. The formation of the films changes with different thicknesses when heated or annealed^[4, 9]. Electrical properties are also affected by *in situ* heating and there have been complications with films less than 30nm when studying some properties^[13]. Factors and events that happen inside the vacuum chamber during film growth are called *in situ*. These properties allow manganese to be used in optoelectric applications and high temperature electronics^[4, 13].

Many studies have been performed on growing thin manganese films by thermal evaporation^[8, 11, 12, 14, 15]. Most of the studies have been performed by similar groups and grow the films between 2-17 Å/s. They have found the bulk resistivity of thin films does not reach the

expected value of bulk material up to several hundred nanometers^[11]. Different rates and growth temperatures have been tested but the accepted bulk film resistivity is $\sim 375\mu\Omega\cdot\text{cm}$.

Hypothesis

The purpose of the study was to find the thickness at which manganese films transition from the properties of the bulk material to nanomaterials. Bulk materials can range from large resources to objects that are used every day in microscale electronics. To a certain point, the critical thickness, the thin film will exhibit the resistivity similar to the bulk manganese, but when quantum confinement effects occur at nanoscale thicknesses, new properties of the film will arise. The thickness of the film at this point will be determined by examining resistivity during and after growth of the film and through comparing the results to theoretical studies involving similar materials. The resistivity (which is constant in bulk materials) of metallic nanoscale films increases as the thickness of the film decreases.

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Chapter 2

Experimental Procedure

The goal of this work was to build a vacuum chamber for growing and studying thin manganese films. This is important for creating better electronic devices that can be used to improve technology. The vacuum chamber was built from manufactured parts and set up for growing films by thermal evaporation. Manganese films were grown at less than 1 atom/sec onto glass substrates that had gold contacts sputtered on. The resistance of the films was measured *in situ* and the growth rate, film thickness, pressure, and deposition temperature were recorded as well.

Materials

The chamber started as several different pieces that could be used to construct the main body of the chamber and the feedthroughs needed for experimentation. Creating the chamber for the purpose of depositing films required placing the feedthroughs in the proper positions and having space to fit the equipment. The chamber parts were all built using stainless steel because it is non-magnetic and is dense, which prevents air from leaking into the chamber. Stainless steel is also resistant to corrosion and can be heated to 700°C to reduce the pressure in the chamber^[1]. Gaskets were used to seal the different parts of the chamber together. Oxygen-free, high conductivity (O.F.H.C.) copper gaskets can only be used one time, but they fit very well and can sustain high temperatures if the chamber becomes hot. O.F.H.C. copper does not have oxides that can damage the gasket when in vacuum and the thermal expansion is similar to that of steel, so the seal will not become loose when the chamber is heated^[1]. Viton gaskets, rubber gaskets made especially for extreme pressure situations, were used in this chamber because it was disassembled several times and the gaskets could be reused. The Viton gaskets are sometimes

difficult to fit in the seal and are more susceptible to decomposing when heated above temperatures of 150°C, which can happen in the chamber. However, Viton lasts longer because of its reusability. Copper had to be used in certain places because of the heating, but the design of the chamber allowed those positions to be mostly permanent on the chamber. Silver plated, stainless steel bolts were used when assembling the vacuum chamber. The plating prevents the bolts from welding to the nuts and flanges when heated or placed under heavy stress for extended periods of time. The bolts have a 12 point head that is easier to access with a wrench than the traditional hex head. These parts made up the beginning of the chamber.

Sample Holder

Thermal evaporation caused the materials being heated to rise upward in a column, so the substrate holder had to be placed at the top of the chamber. Materials rose upward because the crucible only had an opening at the top where the material could rise. This sample holder was created with the ability to

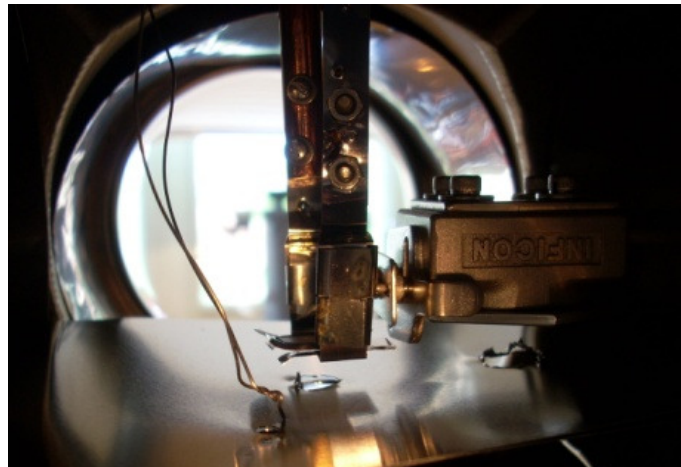


FIG. 1 Tantalum clip sample holder hanging next to the crystal monitor on the right. Thermocouple wires are touching the steel shield to measure the temperature.

hold and heat the sample. Heating the sample was another factor that could be controlled during film growth. Several metals would not work properly at temperatures over 600° C, so Tantalum^[1] was used for its ability to maintain high temperatures without melting or disrupting film growth. Tantalum film was formed into clips and bolted onto thick copper feedthroughs that dissipate the heat and maintain the structure, as seen in Figure 1. A thermocouple was also added

through a mini port in the top of the chamber to measure the temperature of the substrate and the chamber during the deposition. Extra ports on top were blanked with solid flanges to minimize the volume inside the chamber.

An Inficon crystal growth monitor was inserted through a side port that was the same height as the sample holder (Fig. 1). The crystal monitor vibrates at a resonant frequency and detects the deposition of a substance on its surface. As the substance is deposited, the mass affects the frequency of the monitor and certain calibrations allow it to measure the rate and thickness of the film deposition^[2]. A shield was also needed to control the growth of the film so that the substrate would only be exposed when the deposition rate was consistent. Steel shim was used for the shield by mounting a sheet on two rods that were drilled into a flange, and holes were drilled in the shim where the sample was grown and the monitor was placed. Another small piece of shim was placed on a linear motion feedthrough that covered the hole of the substrate. This shield uncovered the hole when growth started and closed as soon as the film was created. Viewing the sample holder and the shields can be very helpful when monitoring the sample so a window flange was added to the top portion of the chamber.

Evaporators

The top of the chamber is where the films were deposited, so the middle portion of the chamber is where the thermal evaporation occurred. Electrical feedthroughs were inserted into the chamber with a basket and a crucible that

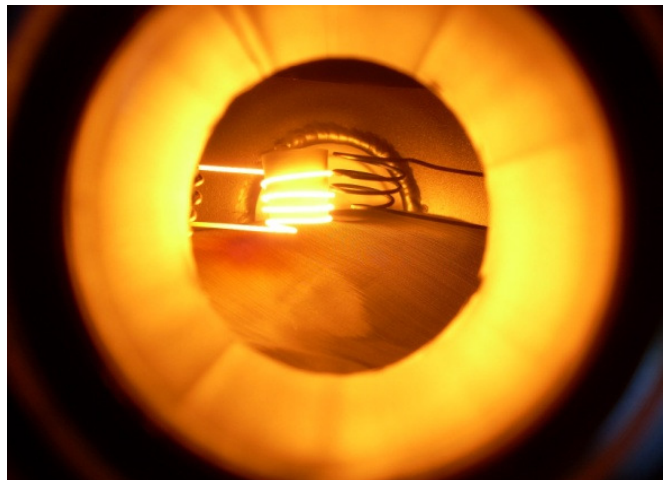


FIG. 2 Crucible being heated in middle portion of chamber. The bright glow represents a temperature around 1200°C.

held the material for evaporation (Fig. 2). The baskets were handmade of Tungsten because they needed to heat up to 1500 Kelvin. The baskets were made by heating the tungsten with a propane torch and wrapping the wire around a half inch bolt. Tungsten baskets were brittle and stiff, but it was much cheaper to make them than buy them. The baskets were attached to the copper feedthroughs by wrapping them with steel foil that was spot welded to hold it all together. Each of these baskets held an insulating crucible^[2] made of quartz (GeO_2) or aluminum oxide (Al_2O_3). These crucibles held the material that was being evaporated. Having a crucible allowed for a controlled upward deposition and the ability to use powders and small crystals that would normally disperse throughout the chamber when evaporated.

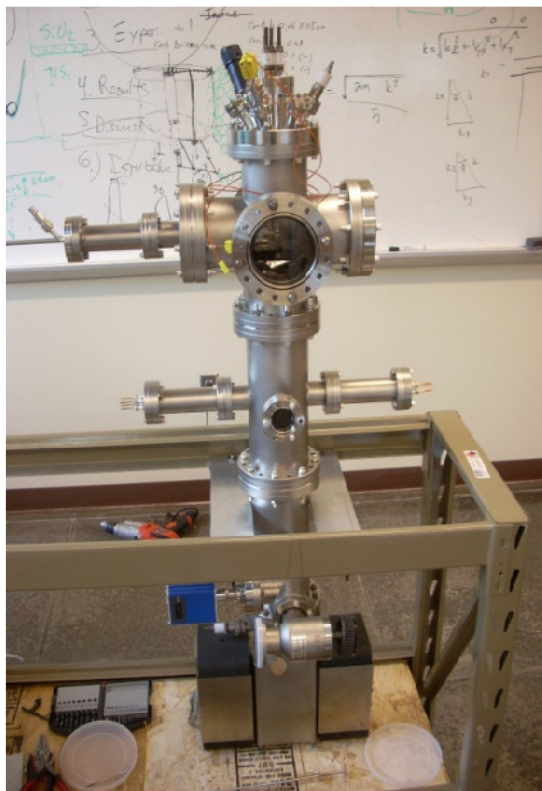


FIG. 3 The assembled vacuum chamber in the metal station platform. This is in the beginning stages of creation.

chamber completed with the above mentioned parts.

Each material used was placed in a compatible crucible for the heating. Three feedthroughs were used in the chamber for evaporation. Having multiple evaporation points was necessary for the multi-layer films and complex growth formulas that were needed. This section of the chamber was expected to become dirty with the different materials that were being evaporated, so precaution was taken in creating a protective layer on the walls of the chamber. A thin steel foil was cut and bent to fit snugly inside the walls of the chamber and protect them from the variety of materials used in the deposition. Figure 3 shows the vacuum

Vacuum System

The top half of the chamber described above was mostly used for the evaporation and growth of the films and the bottom of the chamber did the heavy mechanical work. Two flanges were blanked because they had no use, but could serve as ports to extend capabilities in the future. The pumping system^[2, 3] for the chamber consisted of a roughing pump and a turbo pump. This was built separately and attached by a flexible hose that was not very efficient. The pumping ability decreases as a function of the hose diameter and length. Using the hose was the easiest way to attach the pumps, but it could be changed in the future. A valve was connected to the chamber in front of the pumps so that the vacuum could be sealed and the pump did not have to run constantly to keep vacuum pressure. An ion gauge^[1, 2, 4] was also connected on a tee between the valve and the chamber to measure the pressure of the chamber in Torr (mbar). An ion pump was attached to the bottom of the chamber to lower the pressure and provide a sturdy base. The assembled vacuum chamber was placed on a metal station platform. The chamber was bolted to a plywood shelf and aluminum flat bars were bolted to the top of the frame around the chamber to keep it from tipping.

Improvements

Throughout the course of the research, the vacuum chamber was manipulated and improved to grow better films. In the initial experiments, the chamber became extremely hot when materials were evaporated. This increases the pressure and contaminates the films as they grow. To adjust this problem, several changes were made to create a more sophisticated vacuum chamber shown in Figure 4. The sample holder was adapted to measure electrical properties *in situ* and was able to be heated during or after growth. Better crucibles were installed to hold more material so the chamber would not have to be opened as often to replace the source

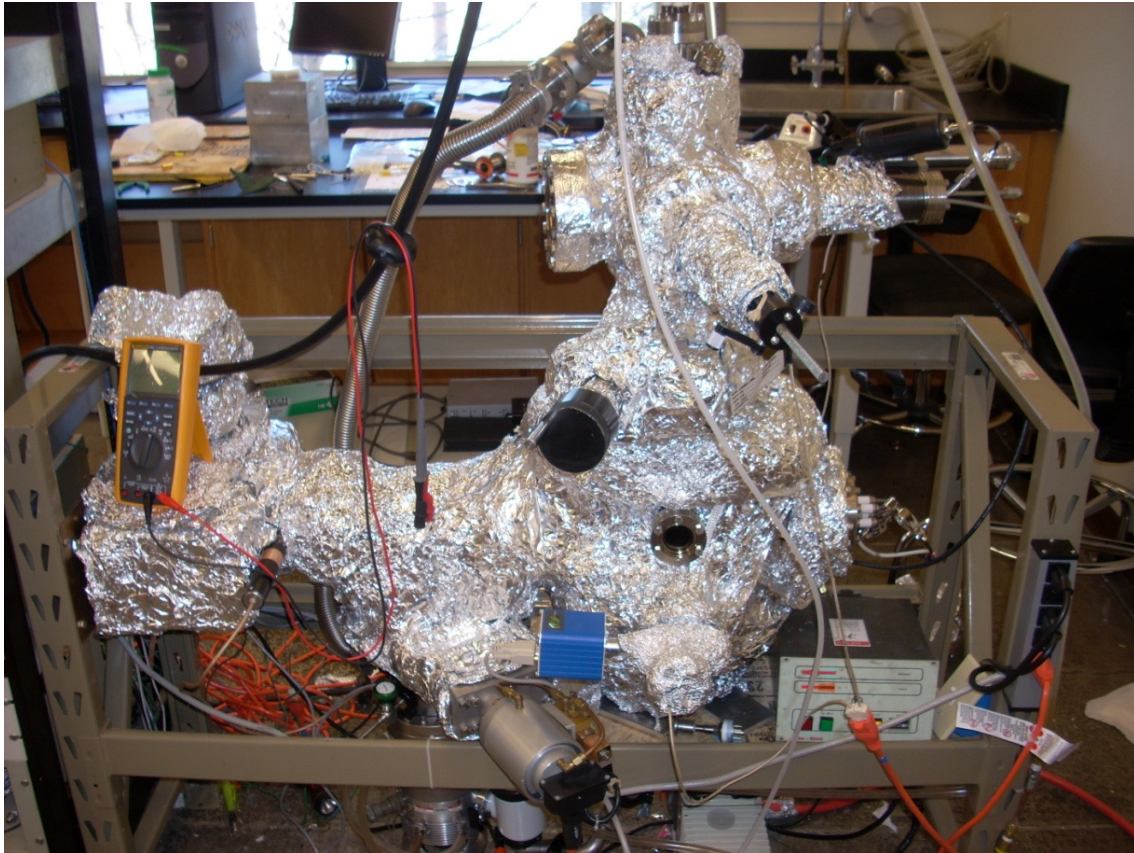


FIG. 4 Sophisticated and improved vacuum chamber for growing pure manganese thin films.

material. Additional pumps were added, such as a titanium source pump and another ion pump, which improve the pressure of the chamber. The turbo pump was connected directly to the chamber instead of being attached by a hose which drastically decreased the pressure. The chamber can also be baked and there is a load lock that makes pumping down the chamber much quicker than before. The chamber was also installed with a water cooling system to keep a consistent temperature. All these changes were made to improve the vacuum chamber. Mostly it lowered the temperature of the chamber to prevent extra outgassing that raised the pressure and contaminated the chamber. The improvements led to a well controlled vacuum chamber that was used for growing the thin films.

Method

For this project, thin manganese films were grown using a method called thermal evaporation (Fig. 5). Thermal evaporation works by heating the source material until it evaporates or sublimates. Atoms are separated from each other in this process. The atoms are then deposited onto the substrate to grow a film. The substrates used were made of glass, but any smooth insulating material could have been used. Each substrate was a glass slide scribed into 1 in x 1 cm strips. They were cleaned with soap, acetone, and ethanol to remove any oils and dirt. The substrates were sputter coated with 30 nm of gold on the sides, which left a 1 cm square in the middle for the manganese to grow. The glass substrate was then inserted into the sample holder clips of the vacuum chamber. The two-point method was used to measure the resistance across the film, so the

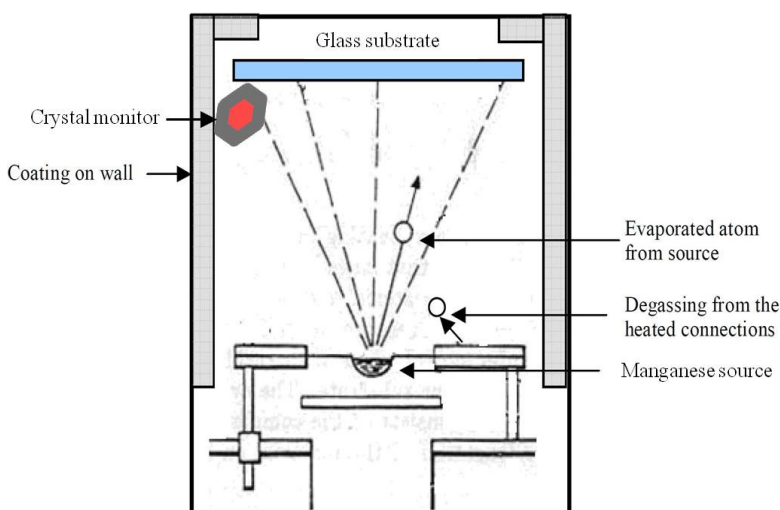


FIG. 5 A visual of thermal evaporation. The heated material rises from the source to deposit on the substrate. The thickness is measured by the crystal monitor.

contact resistance had to be measured prior to inserting the substrate into the chamber each time. A K-type, alumel-chromel, thermocouple was clipped to the back of the substrate to measure the temperature of the film during growth. The substrate was then sealed in the chamber and the load lock was pumped down.

A pressure of 10^{-6} Torr was acquired in the load-lock before opening the gate valve to the lower portion of the chamber that was maintained at 10^{-8} Torr. When equilibrium pressure was at least 10^{-7} Torr, the thermal evaporation growing process began. The Ted Pella #5 Al_2O_3 crucible

was filled with 99.95% manganese pieces from Alfa Aesar and outgassed once inside the chamber. The vacuum chamber properties were carefully recorded and the material was heated slowly with a SCR 20S80 power supply. The source material was heated to over 1000°C until the manganese began to sublime. The manganese atoms separated from the source and rose upward toward the substrate. The crystal monitor measured the thickness of the atoms that were being deposited. When the proper growth rate of manganese atoms was reached and maintained the shield was opened so the atoms could deposit on the glass substrate.

The sample growth conditions including pressure, temperature, growth rate, and film thickness were monitored during the growth of the film. The sample holder was hooked up to a multi-meter that could measure the resistance of the thin film *in situ*. As the films grew, the meter recorded the resistance digitally every second. When the manganese film reached 20 nm, the shield was closed and the power supply was turned down. The power supply was turned down slowly to prevent cracking the crucible that held the source material. After the chamber was cool, the load-lock was vented and the sample holder removed.

The sample was then studied outside of the vacuum chamber. A scanning electron microscope (SEM) was used to verify the composition of the film as manganese and check for any large defects. The films were also examined in an atomic force microscope (AFM). An AFM uses a sharp tip to scan the surface of the film and create a picture of the surface.

The vacuum chamber was built specifically for the growth of thin films by thermal evaporation. It had a main body and several feedthroughs used for the sample holder and the evaporators. There was a pumping system to create vacuum and a heating system for the thermal evaporation. Improvements were made to the initial chamber for better growth conditions. The

films were grown and data was recorded digitally for accurate detailed results. Several tests were completed and the information is compiled in the results.

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Chapter 3

Results and Discussion

The purpose of the project was to build a vacuum chamber for the growth and study of manganese thin films. The films were grown in the vacuum by thermal evaporation and they were analyzed *in situ* and after growth. Films were grown at different rates to see how the electrical properties were affected. The resistance was recorded every second and this data was converted to resistivity because it is an intrinsic property of materials. Resistivity allowed for determining where the films have unique nanoscale properties. These properties can be applicable in semi-conductors, strain gauges, and solar cells. The data gathered were analyzed and graphed to determine the electrical properties of the thin films. A surface analysis was also done by using an AFM to correlate surface and electrical properties to different growth rates.

The results of the experiments show that the resistivity (ρ) of the manganese films decreases exponentially to a critical thickness (t_c) after which it decays as $1/t$. The resistivity is dependent on the growth rate of the film, the surface roughness of the glass, the pressure of the chamber, and the deposition temperature. Fundamental properties of the films were determined by utilizing theory to analyze the results.

Figure 6 displays the log of the resistivity of Mn films as a function of thickness. The curves represent one film that was grown slowly and another film grown three times faster, which is less than or equal to one atom per second. The resistivity of each film decreased at a different rate and also had a different minimum value of resistivity. This clearly shows that the growth rate of thin metal films has a substantial effect on the conductivity of the film.

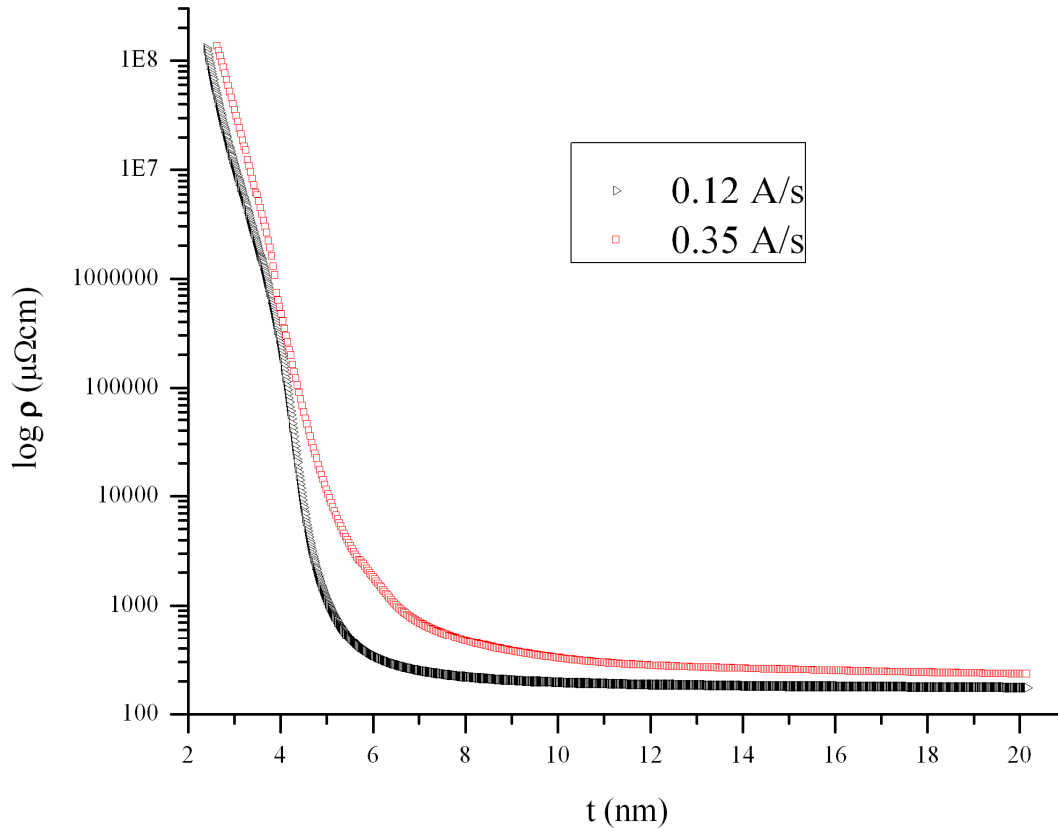


FIG. 6 Log plot of resistivity ρ versus thickness t for Mn films grown on glass slides at different growth rates. The resistivity decreases exponentially to a critical thickness and then decreases more slowly to a minimum value ρ_0 .

The measurements of resistance began at 550 M Ω because the Ohmmeter was limited to this value. As the films grew, the resistivity decreased exponentially, as seen by the straight line with a negative slope at the beginning of each curve in the Log plot of Figure 6. This slope continues at low coverages of the surface and ends when the film reaches a critical thickness. The critical thickness of the film is seen as the angle in the data in Figure 6. Critical thickness is the thickness of the film that determines when the properties of the film change behaviors. After this point, the film behaves differently and the resistivity decreases as t^{-1} . The exact rate of decrease is different for each film and it is expected that the resistivity of all films should continue to decrease until the bulk value resistivity is reached, which is 144 $\mu\Omega\text{cm}$.

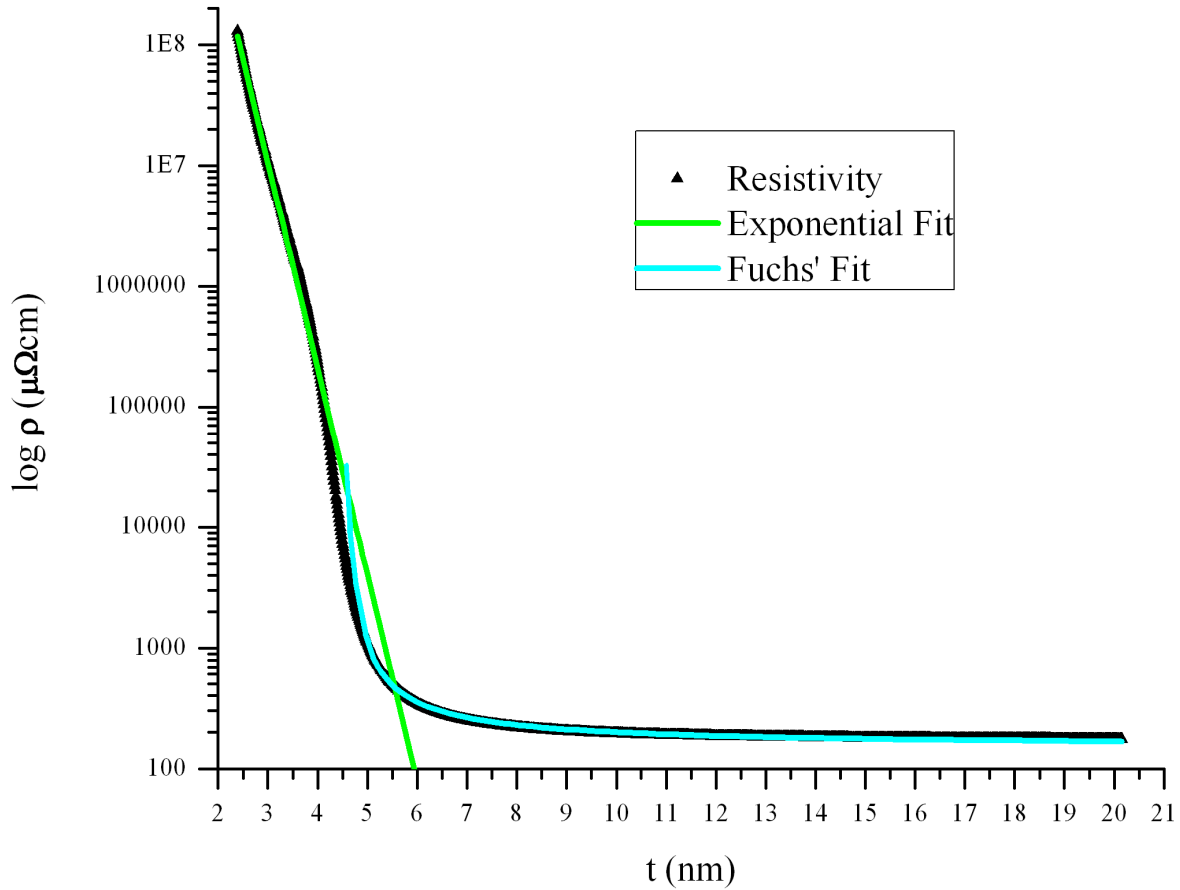


FIG. 7 ▲, Log plot of resistivity vs. thickness for the Mn film grown at 0.12 Å/s; —, fitted exponential curve (Eq. 2) for the discontinuous beginning of the growth; —, Fuchs' fit (Eq. 4) for the continuous part of the growth.

Figure 7 shows a detailed analysis of the manganese film grown at 0.12 Å/s. Even though one film was grown three times faster, both graphs were qualitatively similar and were fit with the same theory, although with different parameters. Two equations were used because there is a transition in the film that cannot be fitted properly with a single curve that describes the whole plot. The left side of the curve that is exponential was fitted with an exponential decay fit:

$$\rho = A_1 e^{\frac{-t}{\lambda_1}}. \quad (2)$$

This fitting curve has two parameters that are used to create the exponential fit. The initial value of the curve is represented by A_1 , which is very large because of the high values of resistivity at the beginning of the curve. The most important value observed from the fitting

curve is λ_I which represents the decay constant of the exponent. The t in the exponent is the measured thickness of the film.

The importance of λ_I is that it defines the slope of the decay which was expected to be the same for any film that would be grown at the same rate with the same conditions. A_I can change for each film because it is dependent on the surface of the substrate and other defects that occur in the film. Through analysis of the data it was found that λ_I changes in an ordered manner depending on the growth rate of the film. As the growth rate increases, the decay constant, λ_I , increases faster than linearly. This was in agreement with previous experimental results by Angadi and Shivaprasad^[1] and the theoretical results of Fuchs and Sondheimer^[2].

Comparing the fitting parameters from each experiment allows for an in-depth analysis and comparison of the films that are grown at different rates. The similarities and differences can be used to determine how the parameters of the fits correlated with other properties of the films, such as their physical structure. Information from each graph has been extracted into Tables 1 and 2 to show how the rates affect the conductivity and growth of the manganese films. Table 1 displays the fitting parameters and important values of the films at low coverages ($t < t_c$).

Table 1

Film	Growth Rate ($\text{\AA}/\text{s}$)	Starting Thickness (nm)	A_1 ($\mu\Omega\cdot\text{cm}$)	λ_1 (nm)
Film 1	0.12	2.390	1.432E12	0.2545
Film 2	0.35	2.615	2.663E12	0.2663

In theory, as the manganese atoms are slowly deposited onto the glass substrate they adhere in the position where they land. The molecules then build up over the substrate and eventually form an even film on the surface. However, in the experiment, each molecule struck the sample with significant kinetic energy that allowed it to move around on the surface and bond with other Mn atoms to form islands that were spotted around the surface^[3, 4]. This pattern

of growth represents the low coverage of the film when the film is not yet continuous. When films are discontinuous, the main mode of transport is tunneling^[5], where electrons jump from island to island along the easiest path. The film is very sensitive to small changes in this stage and the islands are growing quickly so conduction increases exponentially. The islands' diameters grow so that they begin to overlap and create continuous pathways from one side to the other.

Coalescence of these islands leads to a continuous film^[6, 7] where the exponential equation does not fit the data anymore because the film is becoming more bulk-like. The value of thickness where the coalescence occurs is the critical thickness^[3] that causes a transformation in properties as the film becomes continuous. There is a distinct change in the graph at this point and after the critical thickness the plot is fitted with the following curve derived from the theoretical prediction by Fuchs,

$$\frac{\rho}{\rho_0} = 1 + \frac{3(\lambda_0)}{8t}(1 - P). \quad (3)$$

For Fuchs' equation, λ_0 is the mean free path of electrons in the film, t is the thickness of the film, and P is the specularity parameter^[8]. The specularity parameter is the probability that an electron will be reflected backwards when it hits an interface in the film. When the value of P is one, the equation represents a bulk metal in which electrons flow freely. These variables were not able to be calculated individually and the equation was simplified to fit the data plots,

$$\rho = \rho_0 + \frac{C}{t - t_c}. \quad (4)$$

The fitting curve, Eq. 4, has three parameters, where ρ_0 is the bulk value of resistivity for the thin film. The ρ_0 is important to note, because ρ_0 is not the resistivity value of bulk manganese (ρ_{Mn}), ρ_0 is the base value of a thick film. The ρ_0 of thin films is higher than ρ_{Mn}

because of defects occurring in thin film growth that cannot be prevented^[9, 10]. The $t-t_c$ is the thickness minus the critical thickness of the film, and C is a constant constituting the various parameters of specularity, electron mean free path, and temperature in the film^[1, 9, 10, 11],

$$C = \frac{3}{8}\lambda_0(1 - P). \quad (5)$$

There was a correlation in the plots for each rate and the value of C , which determines the decay rate of the resistivity. In the fit equation the value of C is zero when the Mn represents its bulk properties. The values in Table 2 show that as the rate decreased C became smaller which suggests that the film is more like bulk manganese. The ρ_0 also shows that a slower growth rate leads to more continuous films with a minimum resistivity closer to the bulk value. The critical thickness was determined from the value of t_c in the fit curve.

Table 2

Film	Growth Rate (Å/s)	ρ_0 ($\mu\Omega\cdot\text{cm}$)	C ($\mu\Omega\cdot\text{cm}\cdot\text{nm}$)	t_c (nm)	Minimum Resistivity ($\mu\Omega\cdot\text{cm}$)	ρ_{after} ($\mu\Omega\cdot\text{cm}$)
Film 1	0.12	151.63	256.6	4.738	175.6	221.69
Film 2	0.35	191.73	626.9	5.732	221.4	266.50

The data in the Tables were used for explanation when examining the film's external surface properties with non contact mode in the AFM. The pictures in Figure 8 clearly show that films grown at a faster rate (A) have a much rougher surface, than films grown at slower rates (B). Image A is an AFM picture of Film 2 that was grown at 0.35 Å/s and the surface roughness was up to 14.4 nm. Image B shows the surface of Film 1 grown at 0.12 Å/s and the maximum roughness is only 1.4 nm.

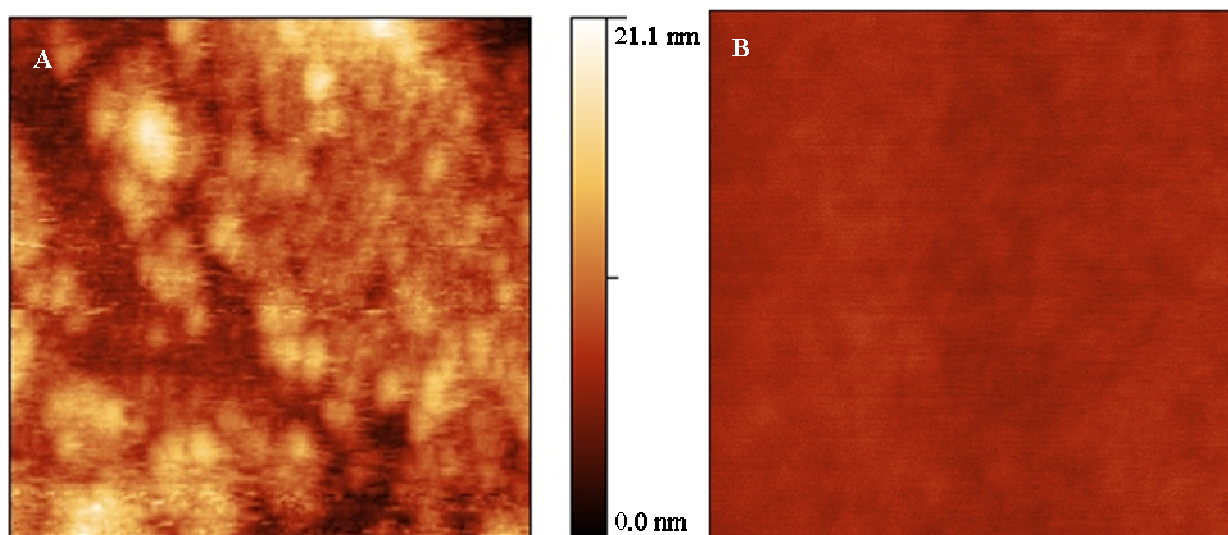


FIG.8 AFM image of Mn films grown at 0.35 Å/s (A) and 0.12 Å/s (B). Both images show a 0.7 μm view of the samples. Image A is much rougher than B.

Nanoscale manganese films were grown by thermal evaporation onto glass substrates. The resistance of the films was measured *in situ* and the data was converted to resistivity and plotted with respect to changing thickness. The data was graphed in Origin 8 and analyzed to show that the growth rate of the film had an effect on the resistivity of each film and the resemblance of bulk manganese. A physical AFM analysis was also used to correlate surface structure to continuity of the films. When films were grown more slowly, they reached the critical thickness more quickly and were much smoother. Slower grown films also reached a lower resistivity that was closer to the bulk value ρ_{Mn} . The higher growth rate created a much rougher film and did not reach as low of a minimum resistivity. Therefore, it can be concluded that growing thin manganese films at a slower growth rate creates a more continuous film.

Another property that was studied was heating the sample after growth to see how the resistivity changed with temperature. Annealing is the process of heating the sample after growth to make the film adhere to the substrate better, and this could be useful to improve the resistivity of thin films. In a discontinuous metal film, the islands will smooth out to lower the resistivity^[11] which has been seen in 100 nm films. However, the film that was heated increased the resistivity

exponentially, as shown in Figure 9. The temperature was raised steadily and the data was fitted with an exponential equation, which is normal for bulk materials. Figure 9 shows more evidence that the thin films were continuous at thicknesses less than 40nm and heating the samples will be continued as a study for future research.

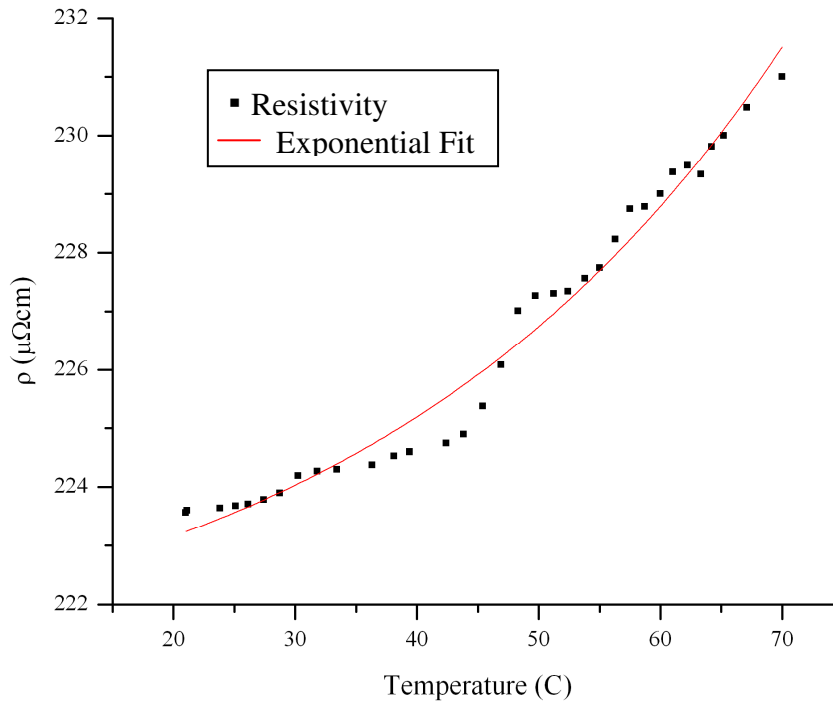


FIG. 9 A plot of resistivity versus temperature after the film was grown to be continued for future work. An exponential growth fit was used to explain the change as temperature increased.

Conclusion

Through the current extent of the research it has been found that the growth rate of thin manganese films has a substantial effect on the change in resistivity as the thickness increases. The slope of the decrease in resistivity decreases as the growth rate of the film increases. This holds true in comparing the slow rates used in this experiment to faster rates studied in the literature^[1]. The growth rate of the film also affects the critical thickness, the minimum thickness at which current can flow through the film, and the minimum resistivity of the film. A slower

growth rate creates a smoother, more continuous film than a faster growth rate when films are grown at room temperature (297K). This result is contrary to the literature in which Angadi and Shivaprasad found that a faster growth rate created more continuous films. They were using rates 10 times faster and did not see clear results in any films less than 10 nanometers in thickness. The bulk film resistivity was also found to be less than $200\ \mu\Omega\cdot\text{cm}$, which is much lower than the $\sim 375\ \mu\Omega\cdot\text{cm}$ determined by Angadi and Shivaprasad^[1, 9].

When the thickness is less than the critical thickness, the film consists of islands that are discontinuous. The current can flow by hopping from island to island. An exponential model is used to explain the changing resistivity in this region. Fuchs' model of increasing resistivity for films with decreasing thickness is generally correct after the coalescing of the islands to create a continuous film. Both models show similar themes when comparing fast and slow growth rates. As the growth rate increased: the starting thickness increased, the slope of resistivity decreased, critical thickness increased, ρ_0 increased, and the roughness increased.

More data points are needed to confirm and expand the explanation of this experiment. It was limited by time available for experimenting. Other persons were using the vacuum chamber for thin films and there were complications that arose during testing that delayed experiments. The project was also limited to a two-point probe, which is simpler but less accurate than a 4-point probe that would have required major modifications. The surface of the film could be examined after the growth, but it would have been helpful to examine each glass surface and see the film structure on the glass because this was an area that had some inconsistency. More films and tests will allow for better explanations and more detailed information.

Future Work

There are other factors that affect the resistivity of thin films as they are growing, and there are interesting effects that occur after the films are grown. Thin films will continue to be grown with varying rates, while testing different materials such as tin and germanium to see how they compare to this study. Other options are to work with different substrates to test how well materials adhere to them and how rates can affect the electrical properties.

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